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TRANSIENT RADIATION-EFFECTS TESTS OF A CORNING RADIATION-RESISTANT OPTICAL FIBER

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Semi-transient and transient radiation-effects tests were performed on a Corning low-loss, radiation-resistant optical fiber. The semi-transient tests, which involved measurement of the fiber transmission during and after irradiation with X-rays, show this fiber to be much more resistant to permanent damage by radiation than other available glass fibers. The transient radiation-effects tests, in which the response of the fiber was measured during and for short times after pulses of X-rays and neutrons, show that the

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fiber may not be applicable to systems that cannot tolerate operational lapses of a few microseconds duration. This is because the fiber emits fluorescent radiation and shows temporary transmission losses during and shortly after pulses of radiation.

Preface

We would like to acknowledge the cooperation of John F. Bryant of the Naval Electronics Laboratory Center for providing the photodetectors used in this work and assisting in the experimental work on the semi-transient radiation-effects tests.

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Transient Radiation-Effects Tests of a Corning Radiation-Resistant Optical Fiber

1. INTRODUCTION

In 1972 Dr. Robert Maurer of Corning Glass Works announced that he had developed a low-loss (less than 10 dB/km) optical fiber that was resistant to nuclear radiation. Tests performed by Dr. Maurer and Dr. Ernst Schiel[1] of ECOM, Ft. Monmouth, showed this fiber to develop much less loss in transmission when irradiated with gamma rays or neutrons than any other glass fiber then available. However, in the tests performed by Drs. Maurer and Schiel, a 2-week period had elapsed between the time of the irradiations and when the post-irradiation transmission measurements were made. During this period, some of the radiation-induced transmission loss could have annealed out. There remained, therefore, questions regarding the short-term and transient effects of radiation on this special Corning fiber.

In 1973 AFCRL was funded by ARPA to investigate the transient radiation effects on the Corning "radiation-resistant" fiber. Because the fiber was experimental, it could not be obtained commercially. Samples of the fiber, designated I-279, were obtained through the courtesy of Dr. Maurer. It is on this fiber that

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1. Maurer, R.D., Schiel, E.J., Kronenberg, S., and Lux, R.A. (1973) Effect of neutron- and gamma-radiation on glass optical waveguides, Appl. Opt. 12:2024.

the tests reported here were performed. All tests were performed on single fibers, not bundles of fibers, and in each test a new fiber sample (not previously irradiated) was used.

2. SEMI-TRANSIENT X-RAY TESTS

2.1 Experimental Setup

The "semi-transient" radiation-effects tests were performed using the AFCRL electron linear accelerator. X-ray pulses 4.5 μs wide were produced by the incidence of 10 MeV electrons on a tungsten target. A 22-m length of the fiber was wound on a 10-cm diam spool and positioned in the X-ray beam. One end of the fiber was coupled to a laser diode and the other end to a photodetector. These were located in a lead shield out of the direct X-ray beam. The laser diode emitted light with a wavelength of 905 nm and was pulsed at a rate of 400 pulses per second. The output of the photodetector (a Texas Instruments TIXL79 silicon avalanche photodiode module) was connected to an oscilloscope where the laser diode light pulses transmitted by the fiber could be observed.

The X-ray dose delivered to the fiber by each accelerator pulse was first estimated by locating a PIN diode in the position to be occupied by the fiber. Thermoluminescent dosimeters (TLD's) were then attached to the spool containing the fiber. The TLD's gave the total dose accumulated by the fiber during the irradiation. By counting the number of accelerator pulses accumulated during the irradiation and dividing the results of the TLD measurements by the total number of pulses, the dose per pulse seen by the fiber was determined. For this irradiation the dose per pulse was 3 rad (Si) per pulse.

2.2 Procedure

The amplitudes of the pulses from the photodetector, which were proportional to the light transmitted by the fiber, were observed while the accelerator was pulsed. Initially, the accelerator was pulsed manually so that any change in fiber transmission could be detected immediately. No changes in transmission were observed during this "single-pulse" operation, so the accelerator was switched to a continuous pulse rate of 20 pulses per second. The photodetector output was observed during the continuous accelerator pulsing, and the accelerator pulses were stopped when any significant change in fiber transmission was indicated. The signal on the oscilloscope was then photographed, and the accelerator pulses started again until the next observable change in transmission occurred. Occasionally during this procedure, a few minutes wait was allowed between the time a significant drop in fiber transmission was observed and restarting the accelerator pulses to determine if there was any short-term recovery of fiber transmission. No such recovery was noticed. Also, the laser diode was turned off for a short time to look for X-ray induced fluorescence in the fiber but none was observed.

2.3 Results

The amplitudes of the pulses from the photodetector, obtained from the oscilloscope photographs, were measured and compared with the amplitude before the irradiation. By dividing the amplitude of the pulses from the photodetector after a specific number of accelerator pulses by the amplitude before irradiation, the relative change in fiber transmission as a function of number of accelerator pulses was obtained. Multiplying the number of accelerator pulses by the dose per pulse (in this case 3 rad/pulse) gave the change in fiber transmission as a function of dose.

The relative changes in fiber transmission were converted to the change in terms of dB/km by the relation:

$$\Delta\,\mathrm{dB/km} = \frac{10\log_{10}(T/T_o)}{L}, \qquad (1)$$

where (T/T_o) is the relative change in transmission determined as described above, and L is the length of fiber (in kilometers) irradiated.

Figure 1 is a plot of the results of these measurements. The extreme nonlinearity of the change in transmission with dose is evident in the change in slope of the plot with increasing accumulated dose. It is also clear that this fiber is much more radiation resistant than other glass fibers for which similar data give much greater initial slopes, as indicated in Table 1.

Table 1. Initial Change in Fiber Transmission (ΔT) per Unit Dose

Fiber	ΔT(dB/km/rad)
Bendix 3551200-75-K2K (note 1)	3.1
Schott LKF	1.6
Rank Hi-Tran	3.4
Corning Low-Loss Type A (note 2)	0.95
Corning I-279	7.4×10^{-3}

Note 1: Bendix fibers are now being manufactured by Galileo Electro Optics. The Bendix name is retained in the table because the fiber was so labeled when tested.
Note 2: Corning now has a low-loss type B which has radiation damage properties similar to the I-279.

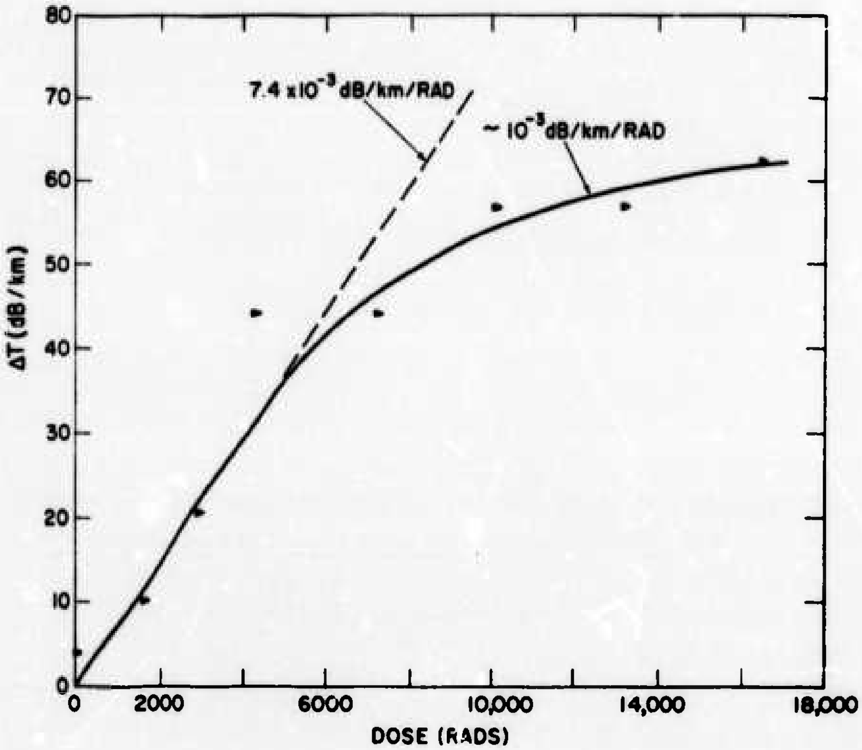

Figure 1. Change in Transmission vs Dose

3. TRANSIENT X-RAY TESTS

3.1 Experimental Setup

The AFCRL 2 MeV flash X-ray machine was used for the transient X-ray tests. This accelerator produces a 20 nsec burst of X-rays with a peak energy of 2 MeV. Similarly to the semi-transient X-ray tests, a 10-m length of the fiber was wound on a 10-cm diam spool and located in the X-ray beam. One end of the fiber was coupled to a photodetector in a lead shield located out of the X-ray beam as previously described, but instead of a laser diode, the other end of the fiber was coupled to a high-intensity monochromator set to a wavelength of 905 nm. The monochromator was used to obtain a constant light source instead of a pulsed source. This was done to avoid the problems and uncertainties associated with synchronizing a pulsed light source with the short flash X-ray pulse. The output of the photodetector was connected to two oscilloscopes with their inputs connected in parallel. One oscilloscope was set for a high sweep speed, so that transients that occurred during and shortly after the X-ray burst could be observed, and the other oscilloscope sweep speed was set to observe longer transients after the burst. Both oscilloscopes were set for dc input so that the constant level of light transmitted by the fiber could be measured. The oscilloscopes were set for single-sweep operation, triggered by the flash X-ray, and equipped with cameras to record the effects of a single X-ray burst.

The dose per burst was measured by thermoluminescent dosimeters attached to the spool containing the fiber. For this irradiation, the dose per burst was measured as 1000 rad.

3.2 Procedure

Prior to the first X-ray burst, the oscilloscopes were triggered by the same source from the flash X-ray machine that would be used during the actual burst. This gave oscilloscope photographs of the photodetector output corresponding to the constant light level transmitted by the fiber under operating conditions. The cameras and oscilloscopes were then reset and the fiber irradiated with an X-ray burst. In addition to the photographs of events during and immediately after the burst, the oscilloscope traces were observed visually a few seconds following the burst to check for any longer term changes in fiber transmission. No loss in transmission was noted from this check, so it was assumed that the fiber had not been significantly damaged. The fiber was then exposed to several more bursts, following the same procedure, with the oscilloscope sweeps set at different speeds. This yielded transient data ranging in time from a few nanoseconds to 10 msec. Also, data were obtained on X-ray induced fluorescence with no light input to the fiber.

3.3 Results

The oscilloscope photographs showed that during the X-ray burst there is a large fluorescent light pulse generated in the fiber. In this experiment, the fluorescent pulse seen by the photodetector was ten times as great as the amplitude of light transmitted by the fiber. The fluorescent pulse decays over a period of several hundred nanoseconds following the burst. Figure 2 was obtained by reading and averaging the data from the photographs and shows the fluorescent pulse and its decay while constant light is incident on one end of the fiber. Figure 3 shows the fluorescent pulse and decay with no light input to the fiber. Curve fits were made to these data with the following results.

With light incident on fiber:

$$A = 47.1\, e^{-0.019t} + 64.1\, e^{-0.0028t} . \qquad (2)$$

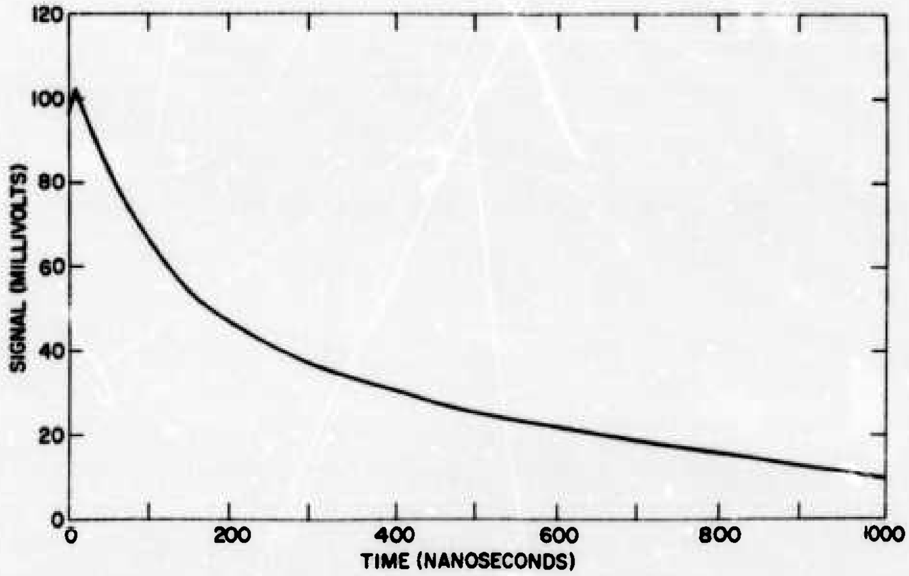

Figure 2. Signal From Photodetector Coupled to Corning 1279 Fiber During and After 1000 rad, 20 nsec, 2 MeV X-ray Burst (with constant light transmitted through fiber)

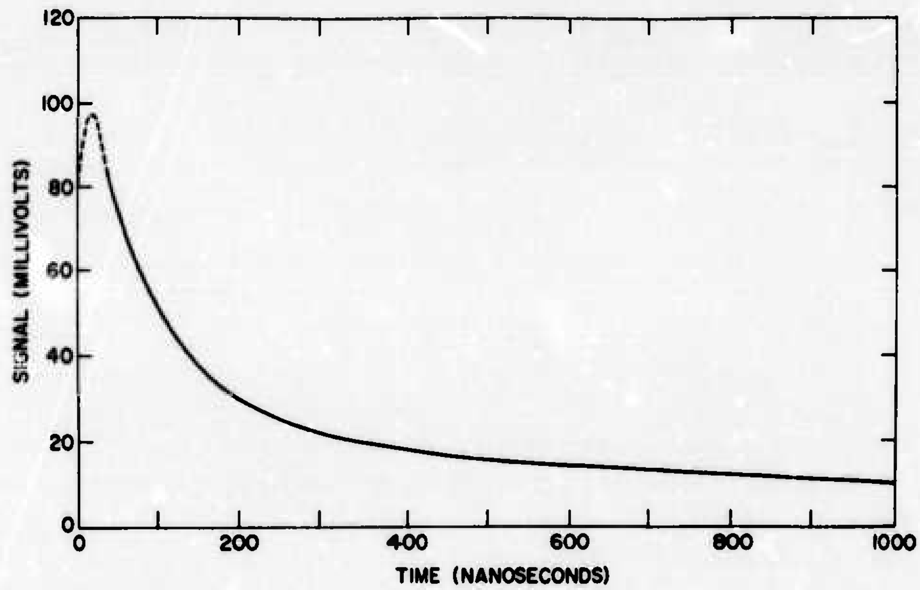

Figure 3. Signal From Photodetector Coupled to Corning 1279 Fiber Due to Light Generated in Fiber by 1000 rad, 20 nsec, 2 MeV X-ray Burst (no light input to fiber)

With no light incident on fiber:

$$A = 110\, e^{-0.015t} + 29.8\, e^{-0.0012t}, \tag{3}$$

where A is the amplitude (in millivolts) of the output of the photodetector due to the fluorescent pulse at time "t" nanoseconds after the burst. In Eq. (1) the fit was made after subtracting the assumed constant signal due to light transmitted by the fiber. As will be seen below, this may not be valid. Therefore, Eq. (2) is probably more representative of the true fluorescent pulse.

The effective magnitude at 905 nm of the fluorescent pulse generated per unit length of fiber was estimated from the detector sensitivity and integrating over the length of the fiber using assumed attenuation coefficients for the fiber. In practical terms, the estimate shows that the detector would see approximately 10 $\mu W/cm^2/m$ of fiber under the conditions of this experiment for a fiber with 10 dB/km attenuation.

As the fluorescent pulse produced by the X-ray burst decays, there is also a loss in fiber transmission that has begun to recover. This is shown in Figure 4, which shows data taken from the oscilloscope photographs for the case with constant light incident on one end of the fiber. At 2 μs following the burst, a minimum signal is observed where the fluorescent pulse has almost fully decayed

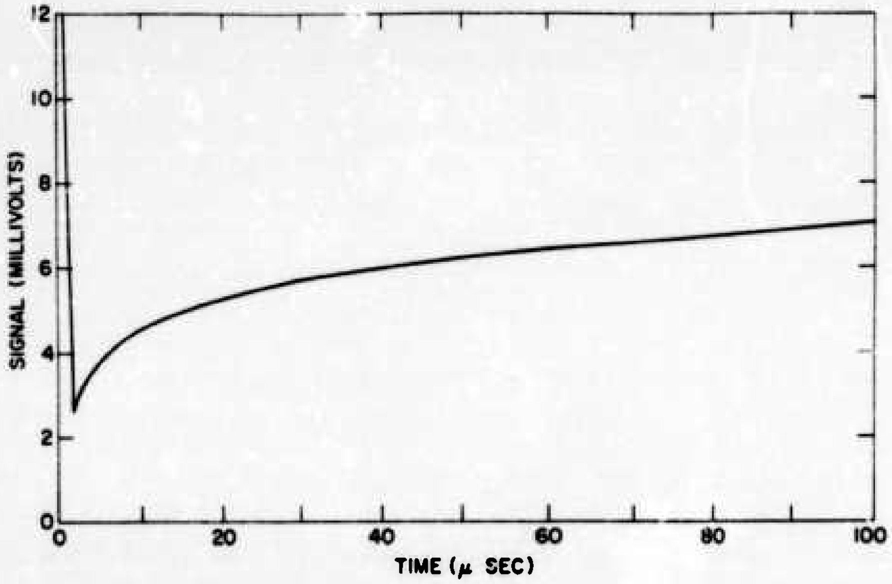

Figure 4. Recovery of Signal From Photodetector Coupled to Corning 1279 Fiber After 1000 rad, 20 nsec, 2 MeV X-ray Burst

but the fiber transmission has not yet recovered. Additional data show that the transmission does not recover to within 90 percent of its original value until 800 μs after the burst.

A fit was also made to these data and gives:

$$v/v_o = 1 - 0.343\, e^{-0.319t} - 0.275\, e^{-0.0224t} - 0.305\, e^{-0.0014t}, \qquad (4)$$

where v/v_o is the ratio of the signal transmitted by the fiber at time "t" microseconds after the burst, to the signal before the burst.

Figure 5 shows the data of Figure 4 in terms of the increase in dB/km over the pre-irradiation value for the fiber as a function of time, as calculated from the data and Eq. (1).

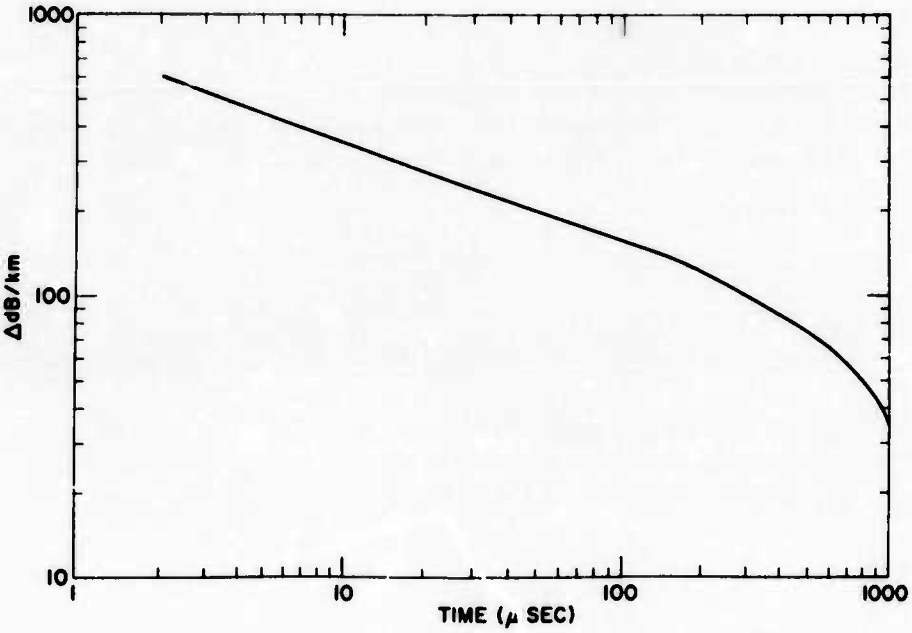

Figure 5. Attenuation vs Time After 1000 rad, 20 nsec, 2 MeV X-ray Burst

Figure 6 is a log-log plot of the transient data over a time span of 10 nsec to 1 msec. This shows the relationship between the fluorescent pulse and the transient loss in transmission more distinctly than the previous linear plots.

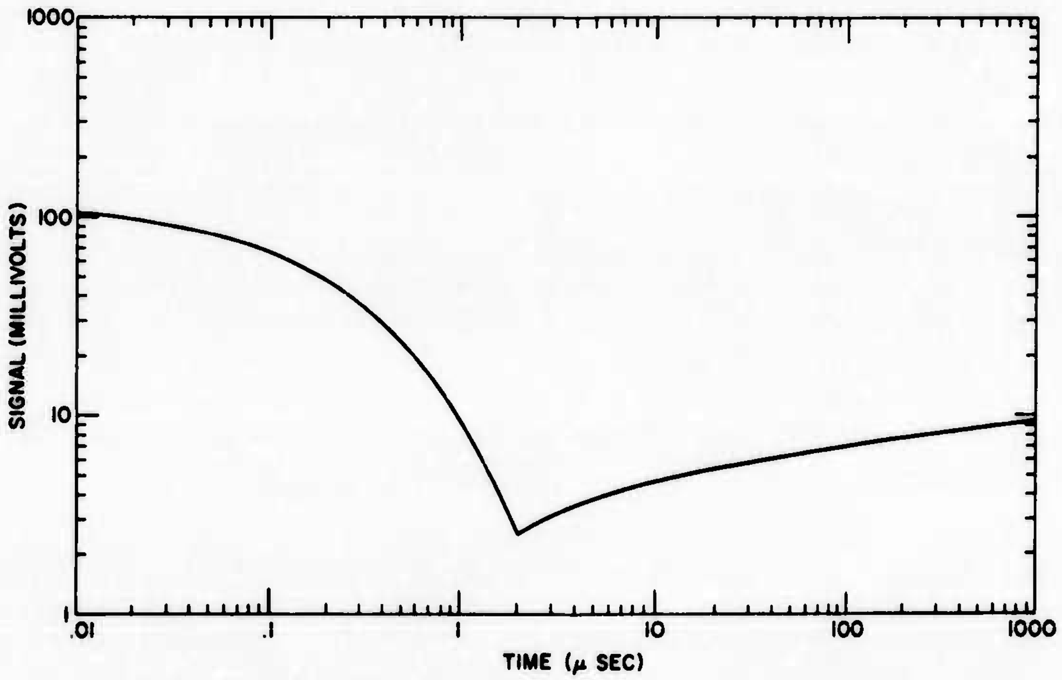

Figure 6. Signal From Photodetector Coupled to Corning 1279 Fiber During and After 1000 rad, 20 nsec, 2 MeV X-ray Burst

4. TRANSIENT NEUTRON TESTS

4.1 Experimental Setup

The transient neutron tests were performed using the fast-burst reactor at White Sands Missile Range, New Mexico. This reactor produces a burst of neutrons that has a gaussian shape in time with a full width at half maximum of 50 μsec. There is also a gamma pulse of the same shape associated with the neutron burst. A 15-m length of the fiber on a 10-cm diam spool was located 1 m from the reactor. One end of the fiber was coupled to a light emitting diode which emitted 905 nm light. The diode was pulsed at a rate of 5×10^5 pulses per second with a pulse width of 1 μsec. The other end of the fiber was connected to a photodetector. The photodetector and light emitting diode were enclosed in a shield (composed of polyethylene, boral, and lead) located about 3 m from the reactor. As in the transient X-ray tests, the output of the photodetector was connected to two oscilloscopes in parallel and set for different sweep speeds. The reactor trigger signal was used to trigger the oscilloscopes in single-sweep mode, while both cameras were manually operated simultaneously to open the shutters just prior to the reactor burst and close them following the burst.

Sulfur pellets and thermoluminescent dosimeters attached to the spool containing the fiber were used for dosimetry. From reactor data, the fiber was located to receive approximately 10^{12} neutrons/cm^2/burst. Following exposure of the fiber, the dose was measured to be 1.04×10^{12} neutrons/cm^2 and 217 gamma rad per burst.

4.2 Procedure

The procedure used was similar to that used for the transient X-ray tests. The amplitude of the signal from the photodetector was photographed before, during, and after the reactor bursts. However, because of interference generated by the reactor and an apparent sudden change in fiber response to the exposures, it was not possible to make repeated detailed measurements as in the case of the X-ray tests.

4.3 Results

The results of the first reactor burst were marred by multiple traces on the oscilloscope photographs due to an error in setting the trigger circuits. However, the fiber response could be faintly discerned behind the multiple traces, and the response to a second burst looked very similar to what could be deduced from the first set of photographs. No change in fiber transmission was observed following either the first or second burst.

The photographs taken during the second burst show what appears to be the leading edge of a fluorescent pulse rising and going off-scale approximately 120 μsec before the burst peak. The amplitude of this pulse would have to be at least 20 MV greater than the signal level, which was 7 MV. (The responsivity of the photodetector used was 2×10^5 MV/MW over an area of 4.6×10^{-3} cm^2.) The duration of the pulse was approximately 30 μsec at its base. Following the pulse is an interval of about .180 μsec duration containing "noise", a large number of pulses of random amplitude, but few larger than the original signal transmitted by the fiber. This interval contains the peak of the reactor burst and ends abruptly near the tail of the burst pulse shape. Following this, the signal transmitted by the fiber continues unchanged in amplitude from its original value.

An attempt was made to determine the amplitude of the fluorescent pulse by reducing the gain of one of the oscilloscopes by a factor of four and exposing the fiber to a third burst. The result of this burst was a very large pulse that completely overloaded and saturated the photodetector. The effect of excessive light incident on the photodetector had been previously tested, and it was found that as the detector became saturated, the response to a light pulse became broadened and suppressed in amplitude. For example, a 100 nsec light pulse with an amplitude of approximately 2 mW/cm^2 incident on the detector produced an output pulse 2 μsec wide with 150 MV amplitude. The detector pulse observed during the third reactor burst was over 450 μsec wide (off scale on the oscilloscope) and 100 MV in amplitude. This suggests a fluorescent pulse that produced several milliwatts per square centimeter at the detector. The amplitude of the signal transmitted by the fiber was recorded within 1 min following the third burst and was unchanged from the amplitude prior to the irradiations.

The source of the large fluorescent pulse observed during the third burst can only be speculated upon. It is possible that the first two neutron irradiations created trapping centers in the fiber. These trapping centers may have bound electrons that were released during the third burst, producing fluorescent radiation. If this is the case, the trapping centers must be non-absorbing for 905 nm light, since no change in fiber transmission was observed following the irradiations. Also, the lifetime of electrons bound in the traps must be long, because the time between reactor bursts is approximately 1 hr (the "turn-around" time of the reactor). Unfortunately, the irradiated fiber was not available immediately for spectral transmission measurements which could give some information regarding the source of the fluorescence. The fiber has been retained at the reactor facility until the neutron-induced radioactivity decays to an acceptable level. Although spectral measurements can be made when the fiber is available, it is possible that by then any neutron-induced traps may have annealed out.

5. SUMMARY OF RESULTS

The results of the transient radiation effects on the Corning I-279 fiber are summarized below:

(1) The fiber is more resistant to moderate-term and long-term transmission loss caused by nuclear radiation than other glass fibers by approximately a factor of 10^3.

(2) When subjected to a burst of X-rays, a fluorescent pulse is generated in the fiber. This pulse decays to negligible intensity in approximately 1 μsec after termination of the X-ray burst.

(3) An X-ray burst also causes a decrease in fiber transmission within the decay time of the fluorescent pulse. The transmission recovers to within 90 percent of its original value in about 800 μsec for a 1000-rad burst.

(4) A neutron burst produced a fluorescent pulse and "noise" in the fiber. The duration of the fluorescent pulse is less than the duration of the burst, but the noise continues throughout the burst.

(5) No loss of transmission was observed immediately following neutron bursts of 10^{12} neutrons/cm^2.

(6) An accumulated neutron irradiation of 2×10^{12} neutrons/cm^2 produces a very large fluorescent pulse in the fiber when it is irradiated with an additional burst of 10^{12} neutrons/cm^2. This pulse is orders of magnitude greater in intensity than those observed in other irradiations of the fiber.

6. CONCLUSIONS

The transient effects of pulsed radiation on a system incorporating the Corning "radiation-resistant" fiber will, of course, depend on factors such as the length of fiber used, the magnitude of the light signal input to the fiber, and the dose and dose-rate to which the fiber is exposed. However, the results of the tests reported here indicate that the system may respond as follows.

For an X-ray or gamma burst:

(1) A false signal may be produced due to fluorescence from the fiber. The duration of this signal would be the duration of the burst plus approximately 1 μsec.

(2) There may be a loss of transmission for the duration of the burst and up to about 1 msec following the burst, depending on the design tolerances related to the fiber attenuation characteristics.

(3) There will be essentially full recovery within 100 msec for accumulated doses of the order of 1000 rad.

For a neutron burst:

(1) There may be a false signal pulse due to fluorescence plus noise (possibly a different manifestation of fluorescence) for the duration of the burst.

(2) Fiber transmission should recover fully within a few microseconds following the burst. (No real loss of transmission was actually observed during the neutron irradiations, but from tests on other fibers it is assumed that there may have been some loss induced in this fiber that was not detectable.)

(3) There could be a large fluorescent pulse produced following the accumulation of the order of 10^{12} neutrons. The magnitude of this pulse could be large enough to damage some photodetectors.

In regard to the significance of the fluorescent pulse produced in the fiber by radiation, it should be noted that in any system using fiber optics, the response of the photodetector to radiation may be more important. For example, while setting up the transient X-ray tests, it was found that the photodetector produced an output signal equivalent to a light pulse sufficient to saturate the detector, even though it was located at a position where the X-ray dose rate was more than three orders of magnitude below the dose-rate to which the fiber would be exposed. It was necessary to shield the detector with 4 in. of lead in this position to eliminate any significant detector response to the radiation. In regard to transient radiation effects, it may be that photodetectors are the "weak links" in fiber optic systems.